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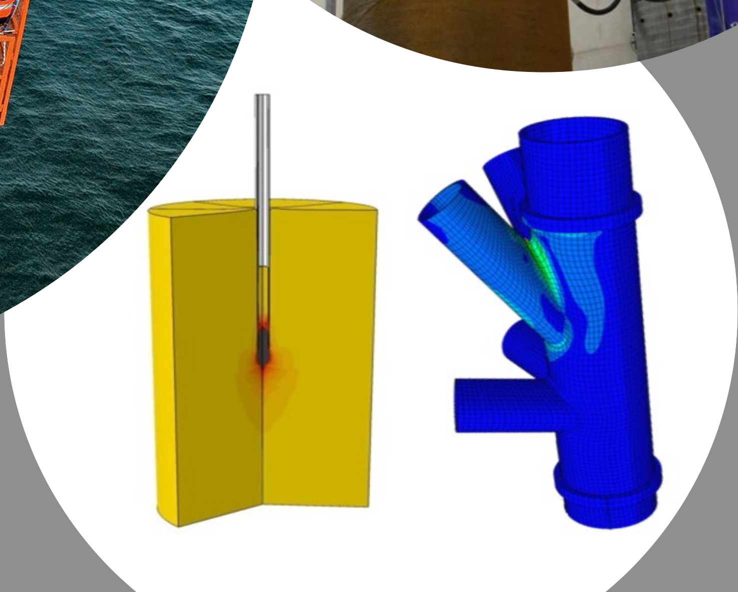
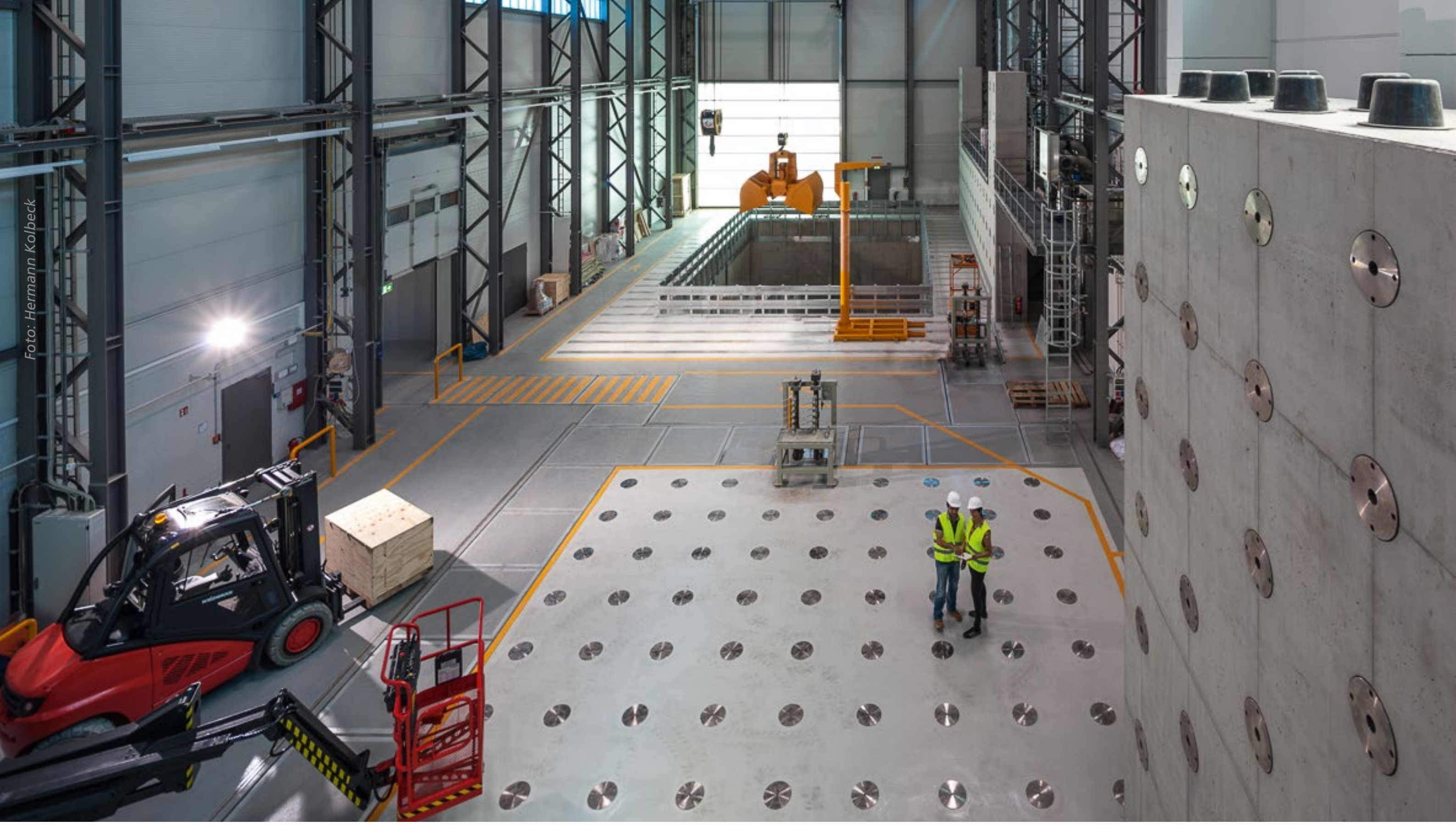
FRAUNHOFER INSTITUTE FOR WIND ENERGY SYSTEMS IWES

TEST CENTER FOR SUPPORT STRUCTURES

Optimization of Design and Construction Methods





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PREFACE

Offshore wind energy is an ecological and economic success story in Europe. The industry has also established itself in Germany, both in the R&D sector (up to 2014, for example, 65% of all patents for the offshore wind industry originated in Germany*) and in the wider economy: in 2015, approximately 143,000 jobs have been supported directly and indirectly by wind energy in Germany alone, generating revenues of more than 13 billion Euros. The installed output in the North Sea and Baltic Sea is already at 5.3 GW, and by 2020 will exceed 7.7 GW according to the federal government's plans**.

In the long-term, the success of the technology fundamentally depends on the competitiveness in the energy market. The price pressure is becoming greater, intensive market consolidation is under way, and also the legal framework in the EU and worldwide is tightening requirements for the optimized use of resources for the entire life cycle of a wind turbine: from initial conception to the planning of cost-effective decommissioning. For European companies especially, the decisive competitive factor is the strength of their research and maintaining or extending their knowledge lead.

To this end, Fraunhofer IWES offers a test environment specifically tailored to the needs of the industry. In conjunction with Leibniz Universität Hannover and the ForWind Center for Wind Energy Research, large-scale physical tests on support structures and their components can be carried out at the Test Center for Support Structures (TTH); on a scale of from 1:10 up to 1:3, or even real scale, depending on dimensions; with individual test forces of up to 2 MN, from simple tensile tests to multi-axial operational stability tests.

A high degree of availability, coupled with a low frequency of service, maintenance, and repairs, is one of the basic requirements for the commercial operation of offshore wind farms. Complex load scenarios due to wind, waves, and turbine operation, restricted access combined with high humidity and salinity of the sea air challenge the technical reliability of wind turbines. It is one of the core considerations for planning, installation, and operation. The further optimization of turbine availability is one of the elementary tasks for the next few years.

The TTH is an integral component of Fraunhofer IWES's overall portfolio. Taken together, the existing test competencies cover the entire offshore wind turbine, starting with the rotor blades, through nacelle components including drive train, the structural components of pile and tower, to the seabed/structure interaction. The TTH's focus is on the experimental validation of models and concepts, but also directly on the qualification of individual parts or entire components. Complemented by geotechnical and engineering know-how in numerical simulation, it helps to reduce technological and commercial risks and achieve accelerated market launch.

* *Study by germanwind GmbH / Windenergie-Agentur WAB; 2014*

** *Acc. to BWE German Wind Energy Association; 01/2018*

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FOUNDATION TEST PIT

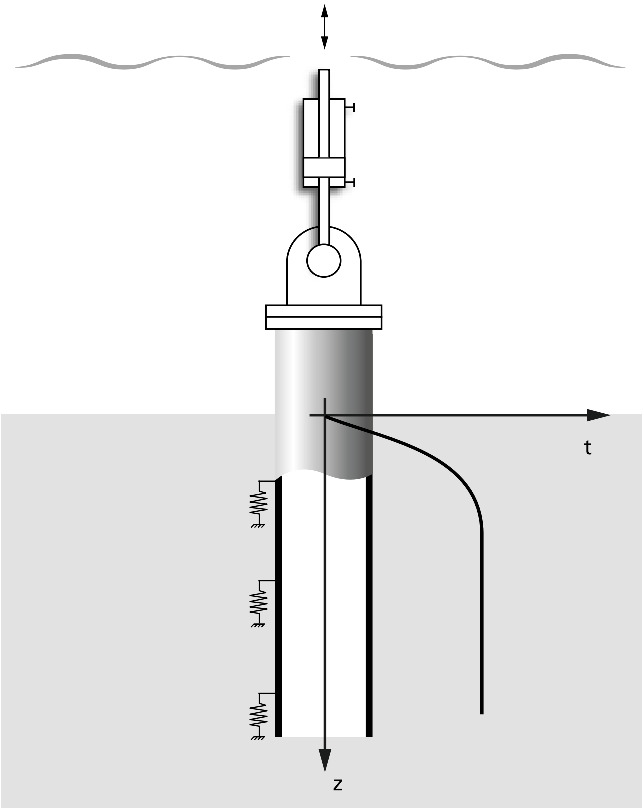
The foundation test pit (FTP) measures 14 m in length, 9 m in width and 10 m in depth, which makes it the world's largest testing facility of its kind. In it, realistic load tests with cyclic and static load application are carried out to examine the behavior of large-scale structural models (on a scale of up to 1:5). The abutment on the long side of the pit as well as various steel frames and angle plates – make it possible to test a wide variety of load scenarios: The structure can be subjected to both single and multi-axial loading via hydraulic cylinders. An analysis of the structural behavior during the test allows conclusions to be drawn about the interactions between the sea floor, the support and foundation structure.

In addition, the FTP also facilitates the testing and assessment of all sorts of pile installation methods, such as impact-driving, vibratory-driving and jacking. Adjustable water level and sand filling level permit reproducible, realistic, homogeneous soil conditions during the test series.

The combination of structural models, numerical calculations, and large-scale experiments make it possible to test and validate new and existing foundation systems, installation methods, and simulation models.

Technical data

- **Dimensions:** 14 x 9 x 10 m (L x W x D); zoning possible
- **Loads up to 2 MN vertically, horizontally, tension & compression**
- **Test frequency:** up to 5 Hz
- **Pit filling material:** ca. 1250 m³ soil (preferably sand)
- **Designed for the employment of pile drivers:** up to an impact energy of 20 kJ per impact



Schematic diagram of a steel pile under axial cyclic loads

„The prospect of industrial scale pile capacity testing at the Test Center for Support Structures will save both time and money for PREON®marines development. The planned testing program will continue to yield invaluable insight into the load bearing behavior of piles installed with realistic loading simulations in offshore environments, using the innovative pile installation technique. The close cooperation between Vallourec and IWES was essential in ensuring the successful completion of the first test phase."

Andreas Lammers
Senior Project Manager
Vallourec Deutschland GmbH

JACKETS AND PILE CLUSTERS PILES UNDER AXIAL LOAD

Despite all their advantages, monopiles have their limitations in certain geotechnical and economic circumstances. For this reason, alternative foundations such as jackets are used at great water depths. These can be founded using individual piles or, as is usually the case with offshore platforms, using pile cluster-based systems. What these structures have in common is that horizontal loads acting on the support structure are transferred into vertical loads on the foundations; therefore, the key design parameter for the piles is their axial load capacity. These tensile and compressive load capacities are determined not only by the pile itself – that is, by its geometry and construction – but also to a large degree by the way in which the pile is installed into the seabed (as well as the properties of the seabed). The diameter of these piles is usually much smaller than that of a monopile, with the result that a whole array of installation methods is possible in addition to driving, for example jacking.

Investigating the impact on the load bearing capacitiy of piles arranged as a dyad

Installation Methods

Investigating alternative foundation variants to the current impact driving is an important topic in the offshore industry. Apart from pure material costs, when implementing the foundation, it is crucial to consider factors such as installation time and effects on the pile load capacity.

For this reason, intensive research is being done in the area of pile-installation. For example, vibratory pile driving is being scrutinized. This offers a possible alternative to the current impact pile driving, because noise emissions and time consumption are much lower by comparison. However, a full picture of the effect of installation on pile load capacity – both on piles under lateral load and under vertical load – is not yet formed which is why vibrated piles are currently impact-driven afterwards. It is hoped that comparisons of vibratory-driven and impact-driven test piles will produce new findings in terms of their global axial and lateral load capacity.

Another new installation method, which is being studied at Fraunhofer IWES in conjunction with an industry partner, is continuous-, jacked piling which demonstrates much higher axial load capacities compared to driven piles, and can therefore be used for jackets, for instance.

„The verification of calculation approaches by realistic model testing is considered unavoidable. For the execution of such experiments, TenneT found an optimal partner in Fraunhofer IWES, which offered ideal testing conditions. The results of the large-scale tests gave us the required planning certainty for our offshore foundations."

Dr. Elmar Wisotzki
Asset Manager Platforms –
TenneT Offshore GmbH

STRUCTURAL HEALTH MONITORING

The reliability of offshore wind turbines is monitored non-stop during operation. To that end, measurements are analyzed, and changes are identified and assessed. Sensors are attached to selected points on the support structure, and sensor function is ensured to guarantee continual and consistent measurements. Benign changes caused by environmental influences and different operating conditions must be differentiated from changes that could, in the long-term, lead to damage; they must be localized and characterized. The systems that can do this are referred to as Structural Health Monitoring (SHM) systems. They should be able to operate automatically, as access is complicated. The analytical methods they use must be geared towards the damage to be expected and enable them to identify benign changes in later operation.

In particular, the ongoing functionality of the measuring technology and the clarity of the evaluation methodology for different types of damage and environmental conditions can be assessed and optimized with the aid of support structure models in the foundation test pit. Causing defined damage to individual support structure components in the clamping field furthermore facilitates the objective and targeted validation of the monitoring system. The combination of structural models, numerical calculations, and large-scale experiments make it possible to test and validate new and existing foundation systems, installation methods and simulation models.

Investigation of the structural dynamic behavior of monopiles

„We investigated in the foundation test pit if damage at the grout connection of monopiles is detected and if it can be distinguished from nonhazardous changes with environmental and operational conditions that evoke very similar signals. Sensors at the tower generated measurement data that was evaluated by routines for signal processing. On the basis of the results, these routines will be improved for further automatization of the system."

Dr. Herbert Friedmann
Manager Research and Development,
Wölfel Engineering GmbH + Co. KG

MONOPILE FOUNDATIONS PILES UNDER LATERAL LOAD

According to WindEurope's findings, more than 80% of all wind turbine foundations that were installed in Europe at the end of 2016 were impact-driven monopiles*. This means that today, and also in the foreseeable future, this is the predominant type of foundation in sandy sea floors, as it offers an array of advantages over alternative systems: this method is a well-established and comparatively cost-effective process; there is an extensive database on load capacities and service life, and little or no groundwork is required on the sea floor. However, installation in greater water depths and wind turbines with capacities up to 10 MW are technically challenging, and require a greater diameter. Large diameters (already up to 8 m by the end of 2016) on the other hand place great demands on the driving technology, and, above all, the design models (e.g.-, the p-y curve method) currently available are, for the most part, no longer directly applicable to these extreme dimensions.

Fraunhofer IWES is collaborating with the industry to conduct in-depth research in the area of design and validation of monopiles. To this end, piles are scaled down to 1:5 to 1:13 based on scaling laws. Subsequently, these are installed in a model sand similar to the offshore construction site and subjected to either static or cyclic lateral loading. During the test, the support behavior is recorded by sensors on the pile (e.g., strain gauge, inclinometer, displacement transducers) and in the soil (e.g.-, earth pressure and pore pressure transducers). Using these, the pile deflection lines and load transfer curves can be reconstructed, analyzed, and compared later. This is used for the further development and validation of models, such as the p-y curve method.

* *The European offshore wind industry / Key trends and statistics 2016, p.23. Report by WindEurope asbl / vzw, available at: https://windeurope.org/wp-content/uploads/files/about-wind/statistics/WindEurope-Annual-Offshore-Statistics-2016.pdf*

Monopiles and tower segments arranged for removal

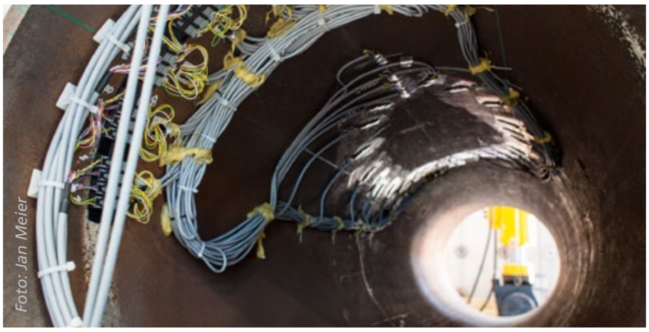
„For Ramboll, the development and improvement of design methods is always of great importance in order to reduce the cost of renewable energy. The large-scale tests conducted within the framework of the TANDEM project at the Test Center for Support Structures are an important component for validating new geotechnical design approaches for offshore wind foundations."

Dr. Andreas Willecke
Head of Department,
Ramboll Wind & Towers – Offshore Wind

HORIZONTAL CLAMPING FIELD FOR LARGE COMPONENTS

Offshore wind turbines are breaking records for power output and dimensions on an ongoing basis. This means that the bases of assessment are as well nearing their limits when it comes to technical rules and standards. Large-scale tests are essential to verify the reliability of components. As the dimensions of the parts increase and load situations during operation become more complex, the test environments must become bigger and more sophisticated as well.

The clamping field (L 18.5 m x W 9.5 m) with its rigidly attached angled walls (L 9.5 m x W 10 m x H 8.0 m) in the Test Center for Support Structures represents a unique test environment in terms of size and variability. The fatigue and load-bearing behavior of components can be tested here. In addition to the massive abutments, welded angle constructions and/or portal frames can be placed anywhere in the clamping field to facilitate the multi-axial testing of any test specimens. A selection of 14 test cylinders in total with maximum loads of 250 kN to 2 MN makes it possible to simulate load scenarios realistically. In order to size a support structure, the focus is often on the transitions and connections between individual areas and elements of the construction. This includes, for instance, grouted joints, which are a hybrid composite of steel and concrete and, as such, create a transition between the foundation pile and the substructure. The joints can be tested in the horizontal clamping field on a large-scale under bending, axial tensile, or compressive forces. Under alternating loads, it is possible to test the fatigue behavior and determine the current damage status. In what is called a jacket foundation, the nodes of the lattice structure are one of the details that are critical to fatigue.



Sensor system for monitoring material fatigue

Welded nodes of a jacket structure prepared for testing

These nodes are usually welded joints with hollow cross-sections. The cyclic testing of a typical node with hollow cross-section in a double-K configuration in the horizontal clamping field of the Test Center for Support Structures is illustrated by way of example. For the test, the joint was scaled down to approximately 1:2.5 and subjected to cyclic loading. In addition to the structural behavior, a further aim of using this demonstrator was to analyze the resistance of a novel coating system to mechanical stresses.

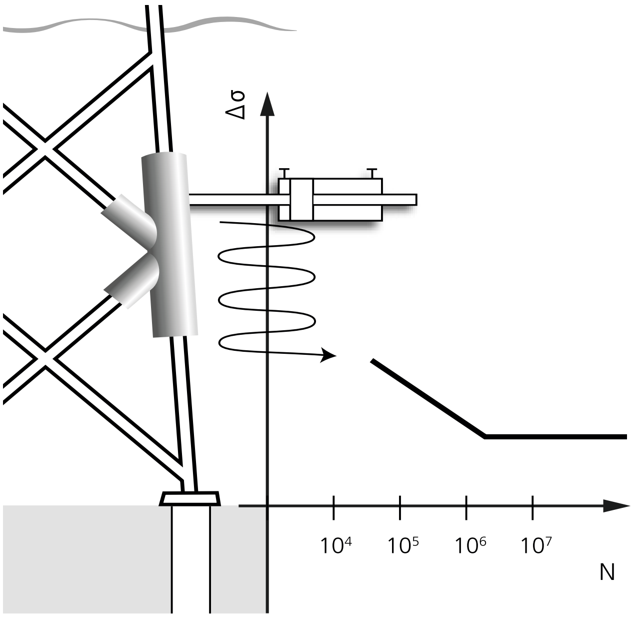


Diagram showing the course of a node test

For onshore wind turbines, the hub height is becoming a determining factor in the economic viability of a location. To ensure the cost-efficient operation of wind turbines even in locations with little wind, the hub height must be increased. Therefore, alternative tower concepts are required. When sizing tubular steel towers, failure due to shell buckling is generally the decisive factor in structural safety. Novel stiffening concepts aim to prevent this. To optimize these, the buckling behavior of tower segments is examined on small- and large-scale test specimens in the horizontal clamping field under static axial and bending loads.

Because only a limited number of large-scale tests can be carried out, it is important to take a full complement of measurements. Only by doing so, it becomes possible to model the test; for example, with the aid of FEM and further analyses. Experience with measuring and strain gauge application technology is therefore essential. This includes measuring stress and strain both using electrical and optical strain gauges, measurement of forces, moments, distances, inclination, accelerations-, and temperatures. The scope of service also includes drawing up a test program and the subsequent preparation and evaluation of the measurements.

Technical data

- **Dimensions of horizontal field:** 18.5 x 9.5 m (L x W)
- **Dimensions of vertical field:** 9.5 x 10 x 8 m (L x W)
- **Angled construction**
- **Load:** 14 cylinders with up to 2MN
- **Test frequency:** up to 5 Hz
- **Anchor points:** 1 MN tension/compression load and 420 kN shear load

„Safety and reliability are the main principles of structural design. Offshore, design often ranges at the proofed limits described in technical rules and standards. Thus, findings from large-scale experiments with dimensions and loading close to reality contributes to design support structures reliably and efficiently.“

Prof. Dr.-Ing. Peter Schaumann
Head of the Institute for
Steel Construction at the
Leibniz Universität Hannover

Jacket foundation of the „alpha-ventus" wind farm

RESONANCE TEST MACHINE ACCELERATED FATIGUE TESTS

To assess the fatigue resistance, structural dimensioning is essentially based on empirical strength curves, referred to as Wöhler curves. For various construction details, these are an integral element of current standards and guidelines and allow comparison of stress level and service life. If the geometry or manufacturing process is changed with the result that they no longer meet the standards, the Wöhler curve of this detail must be determined for commercial application.

In the 1 MN resonance test machine of the Test Center for Support Structures, small-scale tests can be carried out quickly and cost-effectively to determine a Wöhler curve. Also, the resonance test machine is used to carry out large-scale tests on specific construction details. Results can therefore be further corroborated statistically. Standardized material samples, welded joints, and bolts can be tested here at frequencies of up to 120 Hz and a maximum axial test force of 1 MN.

Resonance test machine for determination of a Wöhler curve

Large steel bolts and other standardized materials can be tested

For example, testing a bolt M36 at a test frequency of approximately 55 Hz takes circa 25 hours for 5 million load cycles. To compare, the conventional servo-hydraulic test at a frequency of 10 Hz takes circa 6 days, so the energy costs for such a test would be considerably higher. Therefore, the whole area of high cycle numbers – which is important for support structures – can be investigated quickly and efficiently. The maximum test load of 1 MN also facilitates the testing of large cross-sections. If, for example, a transversely loaded welded joint is regarded as the critical detail in fatigue, joints with a plate thickness of up to 50 mm can be tested.

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